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## Dual modulation of laser diode emission polarization

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Coexisting, switching and bistability of TE/TM-polarizations of radiation of laser diodes with strained active layer has been investigated in [1-4]. The phenomenological model explicating the effect of polarization switching and bistability was developed in [5, 6]. Later on the analytical expressions for polarization switching time were obtained [7]. These expressions allows one to evaluate the influence of different laser diode parameters on polarization switching time.

Laser diodes with switching or bistable polarization of radiation may be extremely useful for data transfer and processing systems, for example, for wavelength division multiplexing systems [8]. It seems to be very important to investigate the possibilities for direct modulation of laser diode emission polarization. The modulation of the state of polarization of the optical carrier can eliminate anisotropic gain saturation (polarization hole burning) in the erbium-doped fiber amplifiers, which can severely degrade the optical signal-to-noise ration in optically-amplified ultra-long lightwave systems [11]. High-speed polarization scramblers are employed in modern optical communicational systems to depolarize the optical carrier launched into the transmission fiber. Semiconductor lasers with depolarized emission are, therefore, very promising devices for optical communication systems because they can be integrated with modulators in a single compact monolithic devices.

In present work the dual modulation (by pump current and confinement factor modulation) possibility is considered to be a method for direct control of radiation polarization. In particular it can be a method to obtain the depolarized laser emission.

The main idea of dual modulation is as follows. The power-current characteristic of the laser diode with polarization switching has a region where degree of polarization and output power are the linear functions of the pump current [7]. Location of this region on power-current characteristic depends, in particular, on optical confinement factor. Thus, it seems possible to change the degree of polarization by confinement factor variation and to keep constant output power by pumping current. The modulation of the confinement factor can be carried out by applying the potential on the side contacts of the laser diode [10].

The system of the rate equations [7] taking into account the confinement factors of TE/TM modes  $\Gamma_{TE/TM}$  is as follows:

$$\begin{aligned} \frac{dN}{dt} &= \frac{I}{qV} - g_{TE} (N - N_{TE}) (1 - \varepsilon_{EE} S_{TE} - \varepsilon_{EM} S_{TM}) S_{TE} - g_{TM} (N - N_{TM}) \\ &\quad \times (1 - \varepsilon_{ME} S_{TE} - \varepsilon_{MM} S_{TM}) S_{TM} - \frac{N}{\tau} \\ \frac{dS_{TE}}{dt} &= \Gamma_{TE} g_{TE} (N - N_{TE}) (1 - \varepsilon_{EE} S_{TE} - \varepsilon_{EM} S_{TM}) S_{TE} + \Gamma_{TE} \beta \frac{N}{\tau} - \frac{S_{TE}}{\tau_{TE}} \\ \frac{dS_{TM}}{dt} &= \Gamma_{TM} g_{TM} (N - N_{TM}) (1 - \varepsilon_{ME} S_{TE} - \varepsilon_{MM} S_{TM}) S_{TM} + \Gamma_{TM} \beta \frac{N}{\tau} - \frac{S_{TM}}{\tau_{TM}} \end{aligned} \quad (1)$$

where  $N$  is the carrier concentration,  $S_{\text{TE/TM}}$  is the density of TE/TM-polarized photons,  $g_{\text{TE/TM}}$  is the linear gain for TE/TM-polarized light,  $\tau_{\text{TE/TM}}$  is the lifetime of TE/TM-polarized photons,  $N_{\text{TE/TM}}$  is the transparency concentration for TE/TM-polarized light,  $\tau$  is the carrier lifetime,  $\varepsilon_{ij}$  are the nonlinear gain coefficients,  $\beta$  is the spontaneous emission coefficient,  $q$  is the elementary charge and  $V$  is the volume of the active medium.

Usually the system of rate equations is analyzed by the numerical methods. This approach can not describe the process dynamics in the explicit form. Authors of [7] have proposed to apply the Lyapunov method [9] to analyze the stability of solutions of the rate equations system. As a result of the analysis the eigenvalues of the rate equations system were obtained. The last represent the characteristic time for transition of the system from one steady state to another. The stability of the system (1) was analysed using the constant carrier density approximation  $dN/dt = 0$ . This condition allows one to perform the very convenient transformation:

$$\begin{aligned} \frac{dS_{\text{TE}}}{dt} &= \Gamma_{\text{TE}} g_{\text{TE}} \left( \frac{I}{qV} - \frac{S_{\text{TE}}}{\Gamma_{\text{TE}} \tau_{\text{TE}}} - \frac{S_{\text{TM}}}{\Gamma_{\text{TM}} \tau_{\text{TM}}} - \frac{N_{\text{TE}}}{\tau} \right) \\ &\quad \times (1 - \varepsilon_{\text{EE}} S_{\text{TE}} - \varepsilon_{\text{EM}} S_{\text{TM}}) S_{\text{TE}} - \frac{S_{\text{TE}}}{\tau_{\text{TE}}} \\ \frac{dS_{\text{TM}}}{dt} &= \Gamma_{\text{TM}} g_{\text{TM}} \left( \frac{I}{qV} - \frac{S_{\text{TE}}}{\Gamma_{\text{TE}} \tau_{\text{TE}}} - \frac{S_{\text{TM}}}{\Gamma_{\text{TM}} \tau_{\text{TM}}} - \frac{N_{\text{TM}}}{\tau} \right) \\ &\quad \times (1 - \varepsilon_{\text{ME}} S_{\text{TE}} - \varepsilon_{\text{MM}} S_{\text{TM}}) S_{\text{TM}} - \frac{S_{\text{TM}}}{\tau_{\text{TM}}} \end{aligned} \quad (2)$$

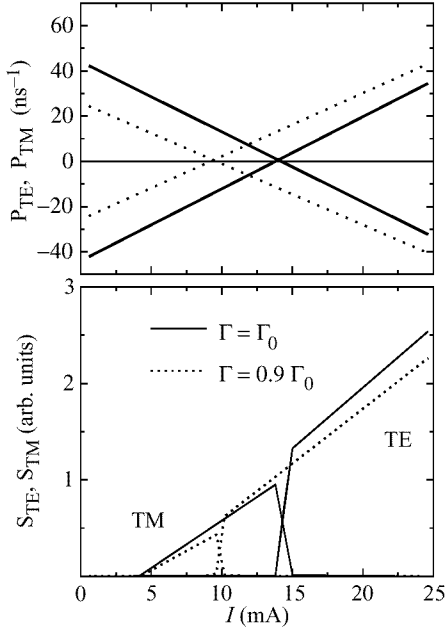
After linearization of the modified rate equations system we can get its eigenvalues named according to [7] stability (instability) coefficients:

$$\begin{aligned} P_{\text{TE/TM}} &= \Gamma_{\text{TE/TM}} g_{\text{TE/TM}} \tau \left( \frac{I}{qV} - \frac{s_{\text{TM/TE}}}{\Gamma_{\text{TM/TE}} \tau_{\text{TM/TE}}} - \frac{N_{\text{TE/TM}}}{\tau} \right) \\ &\quad \times (1 - \varepsilon_{\text{EM/ME}} s_{\text{TM/TE}}) - \frac{1}{\tau_{\text{TE/TM}}} \end{aligned} \quad (3)$$

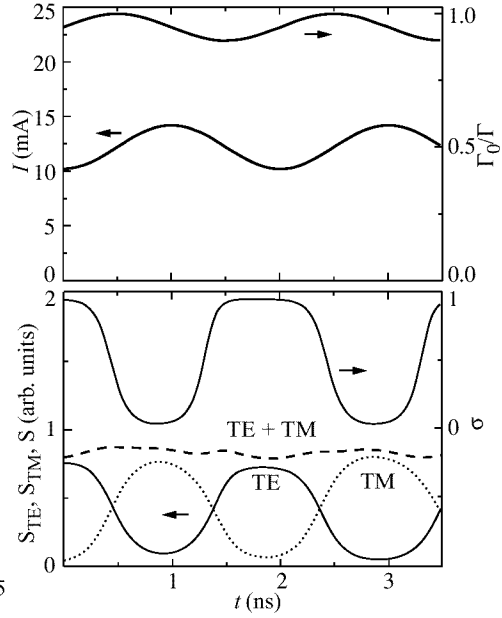
where  $s_{\text{TE/TM}}$  is the TE/TM-polarized photons density in the absence of the photons of another polarization:

$$\begin{aligned} s_{\text{TE/TM}} &= \frac{1}{2} \left[ \frac{1}{\varepsilon_{\text{EE/MM}}} + \Gamma_{\text{TE/TM}} \tau_{\text{TE/TM}} \left( \frac{I}{qV} - \frac{N_{\text{TE/TM}}}{\tau} \right) \right] \\ &\quad - \left\{ \frac{1}{4} \left[ \frac{1}{\varepsilon_{\text{EE/MM}}} + \Gamma_{\text{TE/TM}} \tau_{\text{TE/TM}} \left( \frac{I}{qV} - \frac{N_{\text{TE/TM}}}{\tau} \right) \right]^2 \right. \\ &\quad \left. - \frac{\Gamma_{\text{TE/TM}} \tau_{\text{TE/TM}}}{\varepsilon_{\text{EE/MM}}} \left( \frac{I}{qV} - \frac{N_{\text{TE/TM}}}{\tau} - \frac{1}{\Gamma_{\text{TE/TM}} g_{\text{TE/TM}} \tau_{\text{TE/TM}} \tau} \right) \right\}^{1/2} \end{aligned} \quad (4)$$

As was shown in [7] three combinations of stability coefficients are possible: both coefficients are positive — TE and TM modes coexist; both coefficients are negative — bistable state; and, lastly, the stability coefficients have different signs — in this case the laser diode emits the radiation for which the eigenvalue is negative.



**Fig. 1.** Power-current characteristic and stability coefficients vs pumping current for different confinement factor values.



**Fig. 2.** Time dependence of TE/TM-photon densities and degree of polarization of laser diode radiation for dual modulation. Pumping current and confinement factor modulation is also represented.

Fig. 1 represents the power-current characteristics for TE and TM-polarized radiation for two values of confinement factor  $\Gamma$ . One can see that changing of confinement factors  $\Gamma_{TE/TM}$  allows to change the position of the polarization switching point on the laser diode power-current characteristic (Fig. 1). For laser diode parameters, used in our calculations, the ten percent changing of confinement factor causes the 1.5 times change of polarization switching current. However one can tune the polarization degree of laser diode radiation by modulating of confinement factor and keep the constant output power by pumping current variation (Fig. 2). The relaxation oscillations caused by changing of the confinement factor can be eliminated by appropriate phase shift of the pump current modulation regarding to the phase of  $\Gamma_{TE/TM}$  modulation [10].

In order to simplify the calculations of amplitude of  $\Gamma_{TE/TM}$  modulation, one can determine the polarization switching current  $I_{sw}$ , i.e. the pump current value corresponding to the unpolarized laser diode radiation. The exact value of  $I_{sw}$  can be calculated by putting  $S_{TE} = S_{TM} = S_{sw}$ ,  $dS_{TE}/dt = dS_{TM}/dt = 0$  in (2):

$$I_{sw} = \frac{1}{\Gamma_{TE}g_{TE}\tau_{TE}\tau(1 - \varepsilon_E S_{sw})} + \left( \frac{1}{\tau_{TE}} + \frac{1}{\tau_{TM}} \right) S_{sw} + \frac{N_{TE}}{\tau}$$

$$S_{sw} = B - \sqrt{B^2 - C}$$

$$B = \frac{1}{2} \left( \frac{1}{\varepsilon_E} + \frac{1}{\varepsilon_M} + \frac{1}{\Gamma_{TE}g_{TE}\tau_{TE}\varepsilon_E\Delta N} - \frac{1}{\Gamma_{TM}g_{TM}\tau_{TM}\varepsilon_M\Delta N} \right)$$

$$C = \frac{1}{\varepsilon_E \varepsilon_M} \left[ 1 + \left( \frac{1}{\Gamma_{TE} g_{TE} \tau_{TE}} - \frac{1}{\Gamma_{TM} g_{TM} \tau_{TM}} \right) \Delta N \right] \quad (5)$$

$$\varepsilon_E = \varepsilon_{EE} + \varepsilon_{EM}, \quad \varepsilon_M = \varepsilon_{MM} + \varepsilon_{ME}, \quad \Delta N = N_{TE} - N_{TM}$$

The polarization switching region caused by modulation of  $\Gamma_{TE/TM}$  is limited by the values of switching current corresponding to the minimum and maximum values of  $\Gamma$ . It must be noted that the hysteresis on power current characteristic of the laser diode [7] can substantially decrease the width of the polarization switching region defined by (5).

In summary, we have considered the laser diode dual modulation (by pump current and confinement factor variation) possibility to be a method to control the polarization of the laser radiation. The carried out mathematical modelling of the laser diode under the dual modulation proved the possibility of direct control of laser radiation polarization keeping the output power near to be constant.

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## Appendix 1

Laser diode parameters used in calculations were as follows [7]:

$$g_{TE} = 1.45 \times 10^{-6} \text{ cm}^3/\text{s}, \quad g_{TM} = 1.40 \times 10^{-6} \text{ cm}^3/\text{s}, \quad \tau_{TE} = 2.0 \text{ ps}, \quad \tau_{TM} = 1.61 \text{ ps}, \\ N_{TE} = 4.5 \times 10^{17} \text{ cm}^{-3}, \quad N_{TM} = 3.29 \times 10^{17} \text{ cm}^{-3}, \quad \tau = 3 \text{ ns}, \quad \varepsilon_{EM} = 2.0 \times 10^{-17} \text{ cm}^3, \\ \varepsilon_{EE} = 1.0 \times 10^{-17} \text{ cm}^3, \quad \varepsilon_{ME} = 4.5 \times 10^{-17} \text{ cm}^3, \quad \varepsilon_{MM} = 6.0 \times 10^{-17} \text{ cm}^3.$$

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